Measurement of jet properties and their modification in heavy-ion collisions

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Can the QGP be found using two-particles azimuthal correlations?

NO!

It was already discovered using an ElectroMagnetic Calorimeter!

Partonic degree of freedom in HI at RHIC

Highlights from RHIC AuAu program:

- high-p_T particle yield suppression – jet quenching
- disappearance of the back-to-back jet in central collisions
- exceedingly large azimuthal anisotropy v_2

Finally we observed something, however…

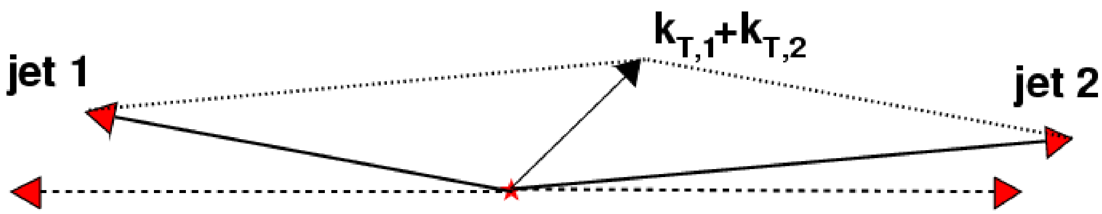
Detailed analysis of parton/jet properties like:

- shape of the fragmentation $D(z)$ and parton distribution function $f_q(p_{Tq})$
- parton transverse momentum $\langle k_T^2 \rangle$

and their modification is vital for understanding of the mechanism of parton interaction with QCD medium formed at RHIC

Hard scattering

Hard scattering in transverse plane



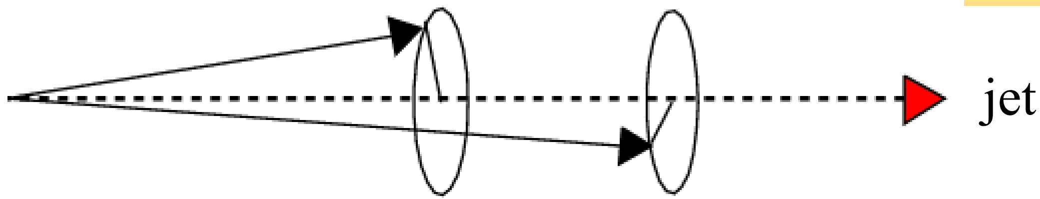
Point-like partons ⇒ elastic scattering $\vec{p}_{T,jet1} + \vec{p}_{T,jet2} = \vec{0}$

Partons have intrinsic transverse momentum $\boldsymbol{k_T}$ $\vec{p}_{T,jet1} + \vec{p}_{T,jet2} = \vec{k}_{T,1} + \vec{k}_{T,2}$

Jet Fragmentation (width of the jet cone)

Partons have to materialize (fragment) in colorless world

$\vec{j}_T =$ jet fragmentation transverse momentum



j_T and k_T are 2D vectors. We measure the mean value of its projection into the transverse plane $\langle|j_{Ty}|\rangle$ and $\langle|k_{Ty}|\rangle$.

$$\boxed{\langle|\,k_{Ty}\,|\rangle = \sqrt{\frac{2}{\pi}}\sqrt{\langle k^2{}_T\rangle}}$$

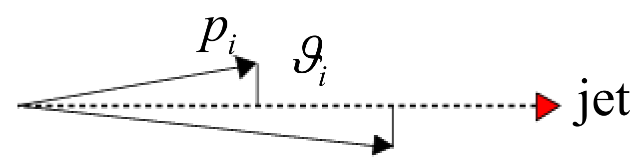
$\langle|j_{Ty}|\rangle$ is an important jet parameter. It's constant value independent on fragment's p_T is characteristic of jet fragmentation (j_T-scaling).

$\langle|k_{Ty}|\rangle$ (intrinsic + NLO radiative corrections) carries the information on the parton interaction with QCD medium.

$$\boxed{\langle k_\perp{}^2\rangle_{AA} = \langle k_\perp{}^2\rangle_{vac} + \langle k_\perp{}^2\rangle_{IS\ nucl} + \langle k_\perp{}^2\rangle_{FS\ nucl}}$$

p+p p+A A+A

Fragmentation Function (distribution of parton momentum among fragments)



In Principle

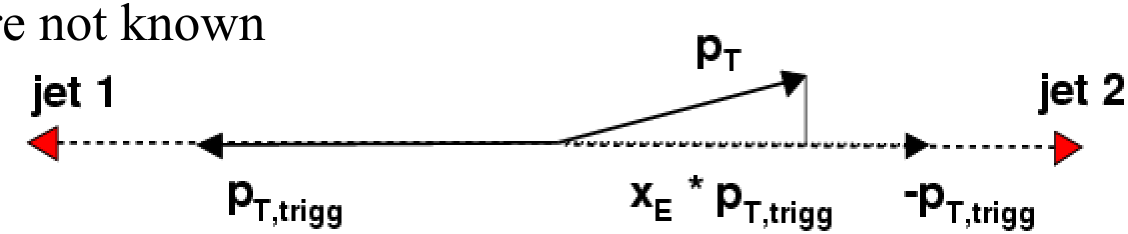
$$\vec{p}_{parton} = \sum_i \vec{p}_i \qquad |\vec{p}_{parton}| = \sum_i |\vec{p}_i| \cos(\vartheta_{\mathrm{i}})$$

$$z_i = \frac{|\vec{p}_i| \cos(\vartheta_{\mathrm{i}})}{|\vec{p}_{parton}|} \qquad \sum_i z_i = 1$$

$$\boxed{\text{Fragmentation function} \quad D(z) \propto e^{-z/\langle z \rangle}}$$

In Practice parton momenta are not known

$$x_E = -\frac{\vec{p}_T \cdot \vec{p}_{Ttrigg}}{|\vec{p}_{Ttrigg}|^2}$$



$$x_E z_{trigg} = \frac{p_T \cos(\Delta\varphi)}{p_{parton}} = z$$

$\Rightarrow$ Simple relation $\boxed{\langle z \rangle = \langle x_E \rangle \langle z_{trigg} \rangle}$

x_E in pp collisions

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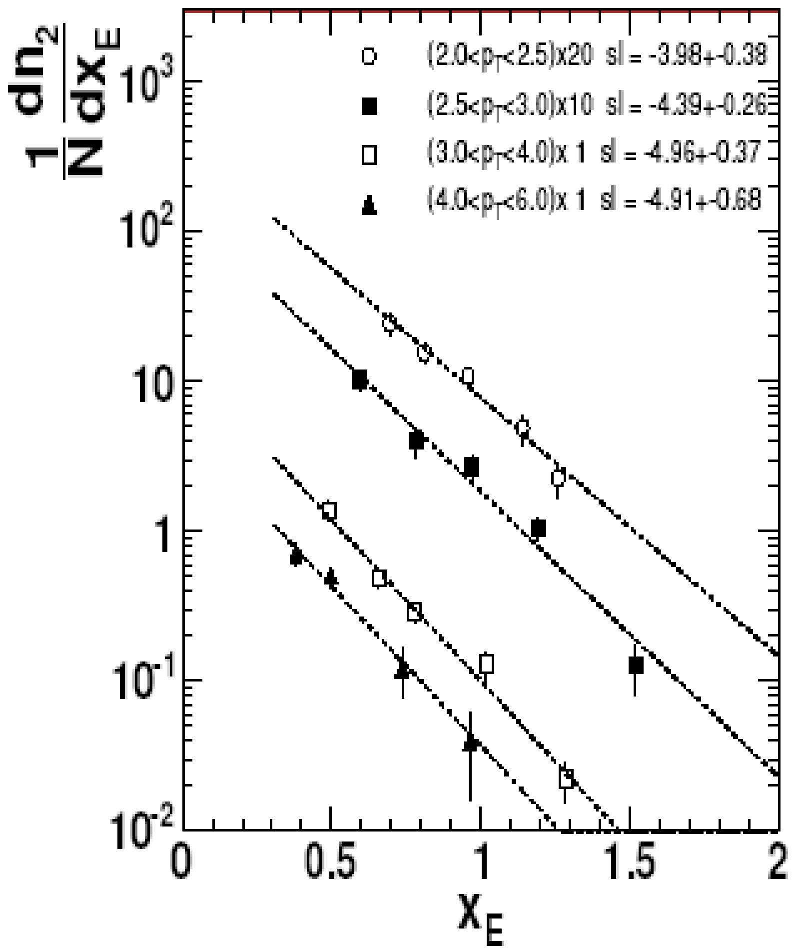
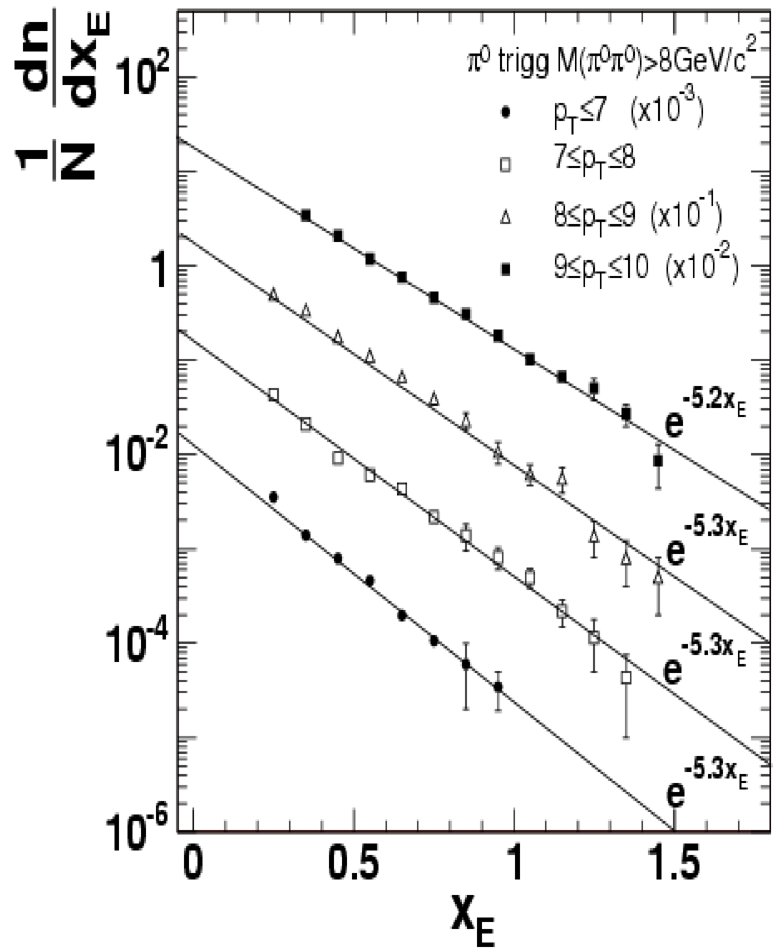


$1/\langle x_E\rangle \approx -4$ to -5

CCOR (ISR) $\sqrt{s}$ = 63 GeV

see A.L.S. Angelis, Nucl Phys B209 (1982)



$1/\langle x_E\rangle \approx -5.3$

$\langle z \rangle$ extracted from pp data

We measured x_E and

$$\langle z \rangle = \langle x_E \rangle \langle z_{trigg} \rangle$$

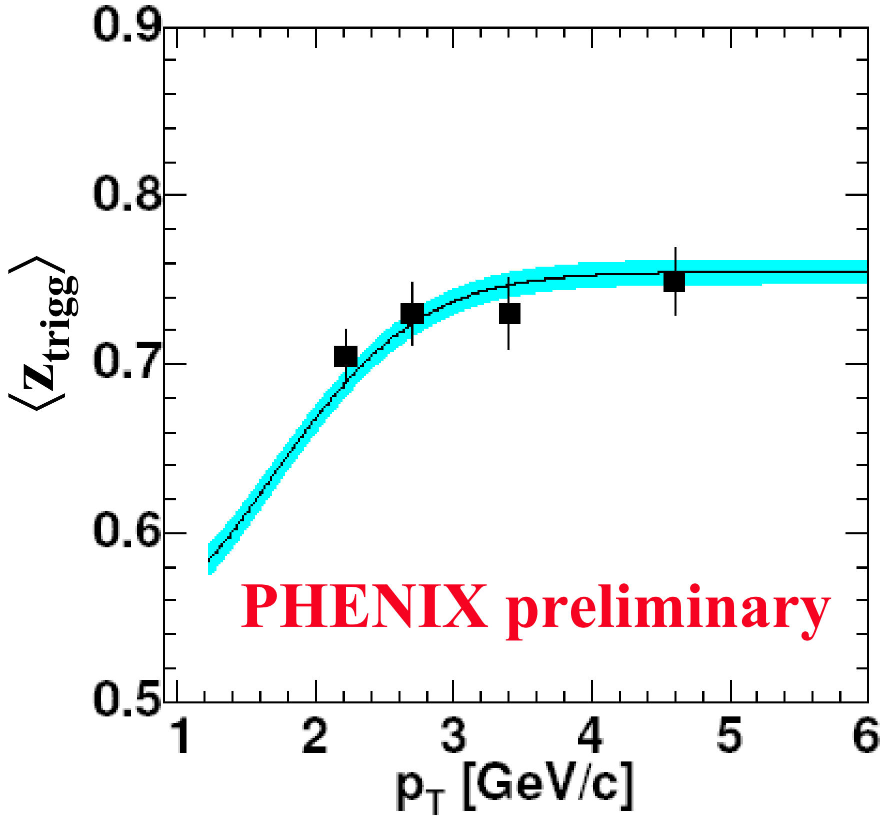
$x_{Ttrigg} = 2.p_{Ttrigg}/\sqrt{s}$

$$\langle z_{trigg} \rangle \propto \int_{x_{Ttrigg}}^{1} z \cdot e^{-z/\langle z \rangle} f_q(p_T / z) \cdot z^{-2} dz$$

Only one unknown variable $\langle z \rangle$ $\Rightarrow$ iterative solution

FFn $D(z)$

final state parton distrib. extracted from PHENIX $p+p \to \pi^0 + X$

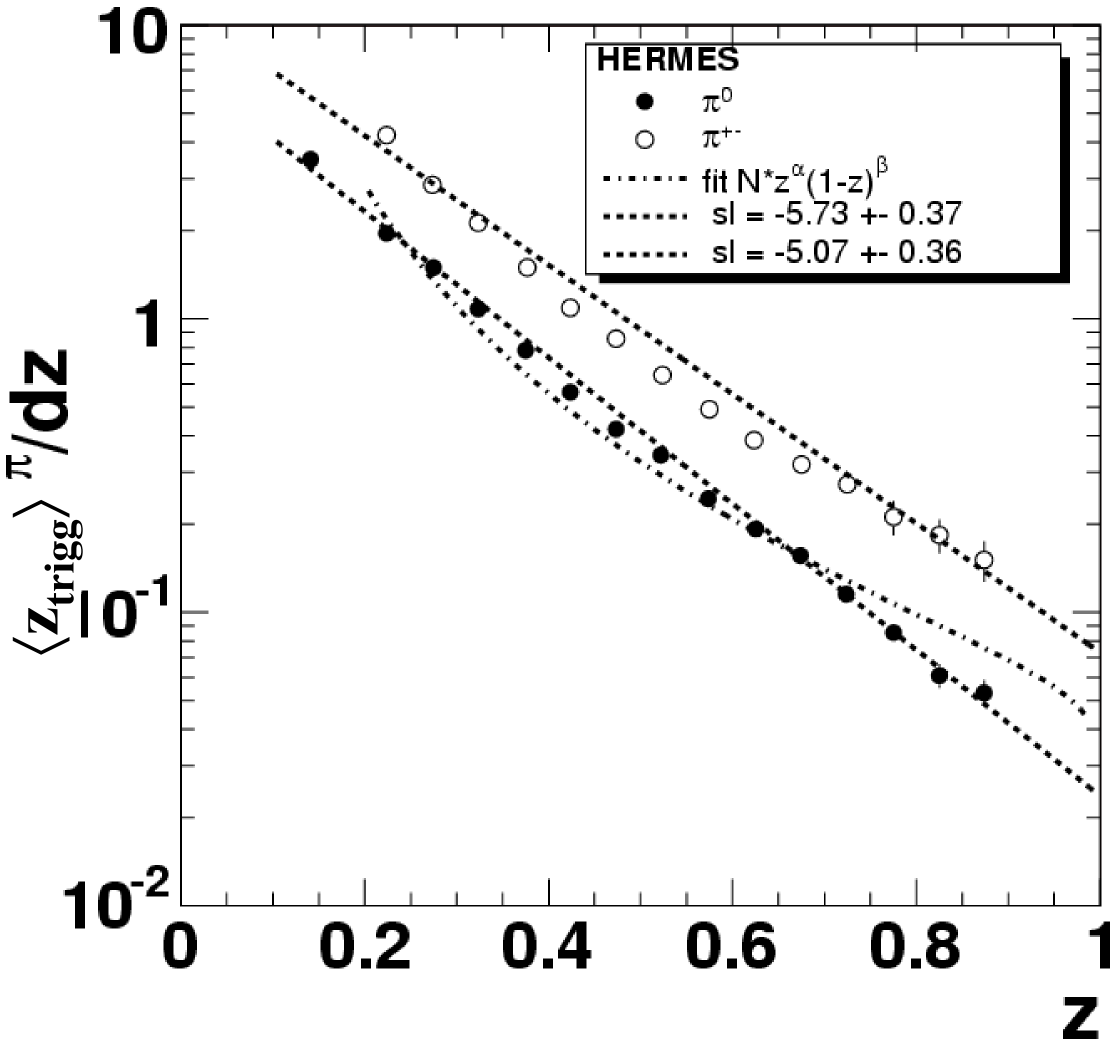


Slope of the fragmentation function in p+p collisions at $\sqrt{s}$=200 GeV

$$\frac{1}{\langle z \rangle} = 6.16 \pm 0.32$$

HERMES fragmentation fcn

A. Airapetian, et. al., Eur. Phys. J. C 21, 599–606 (2001)



DIS of 27.5 GeV positrons on hydrogen.

$z^a(1-z)^b$ parametrization

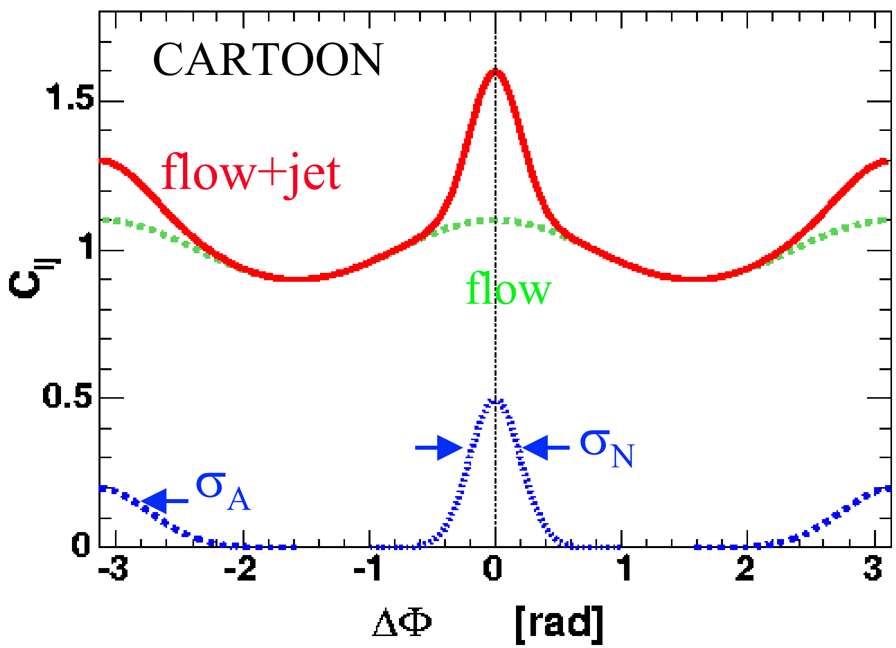
$$\frac{1}{\langle z\rangle} = 5.73 \pm 0.37$$

Method – azimuthal correlation function

Now we know the $\langle z \rangle$ - let us measure σ_N and σ_N.
Two particle azimuthal correlation function →

$$C_{ij}(\Delta\phi) = norm \cdot \frac{dN^{real}_{ij}}{d\Delta\phi_{ij}} \Big/ \frac{dN^{mixed}_{ij}}{d\Delta\phi_{ij}}$$

Unavoidable source of two particle correlations in HI – elliptic flow



"flow" pairs :

$$[1+2v_2^2 \cos(2\Delta\varphi)]$$

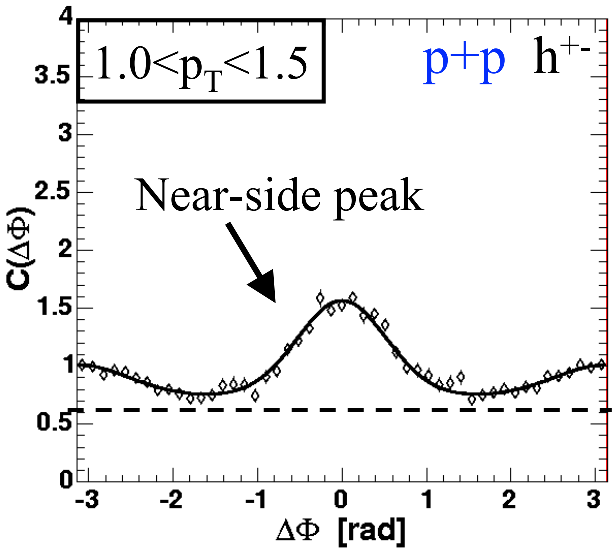
Intra-jet pairs angular width :

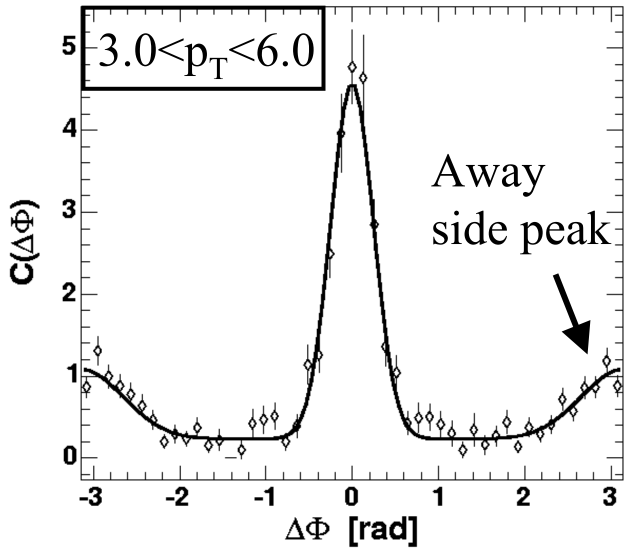
$$\sigma_N \rightarrow \langle |j_{Ty}| \rangle$$

Inter-jet pairs angular width :

$$\sigma_A \rightarrow \langle |j_{Ty}| \rangle \oplus \langle |k_{Ty}| \rangle$$

pp and dAu correlation functions



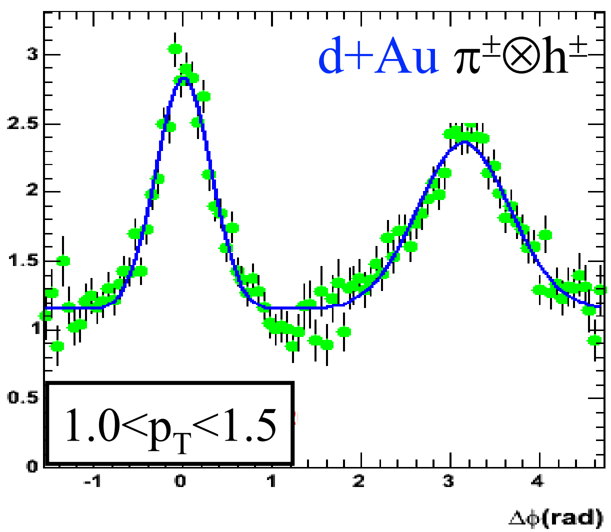


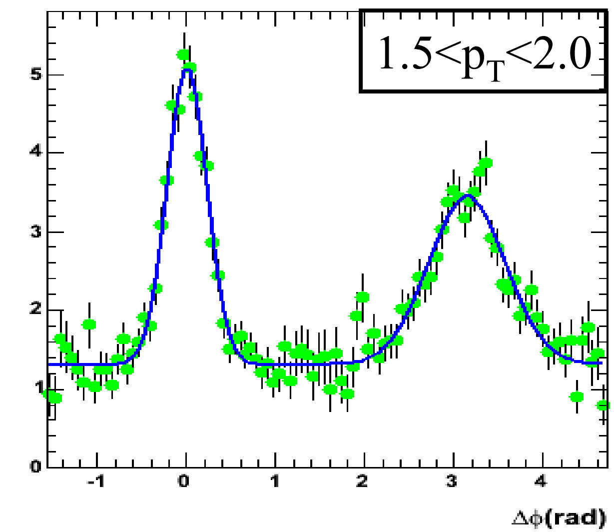
Fixed correlation:

both p_{Ttrigg} and p_{Tassoc} are in the same range

Assorted correlation:

p_{Ttrigg} and p_{Tassoc} different





$5.0<p_{Ttrigg}<16.0$ GeV/c

Jet function assumed to be Gaussian

$$C_{ij}(\Delta\phi) = norm \cdot \frac{dN^{real}_{ij}}{d\Delta\phi_{ij}} \Big/ \frac{dN^{mixed}_{ij}}{d\Delta\phi_{ij}}$$

$\rightarrow$ Fit = const + Gauss(0)+Gauss(±π)

σ_N, σ_A , $\langle|j_{Ty}|\rangle$, $\langle|k_{Ty}|\rangle$ relations

Knowing σ_N and σ_A it is straightforward to extract $\langle|j_{Ty}|\rangle$ and $\langle z_{trigg}\rangle\langle|k_{Ty}|\rangle$

In the high-p_T limit ($p_T \gg \langle|j_{Ty}|\rangle$ and $p_T \gg \langle|k_{Ty}|\rangle$)

$$\langle|j_{\perp y}|\rangle = \sqrt{\frac{2}{\pi}}\frac{\langle p_{Ttrig}\rangle\langle p_{Tassoc}\rangle}{\sqrt{\langle p_{Ttrig}\rangle^2 + \langle p_{Tassoc}\rangle^2}}\sigma_N$$

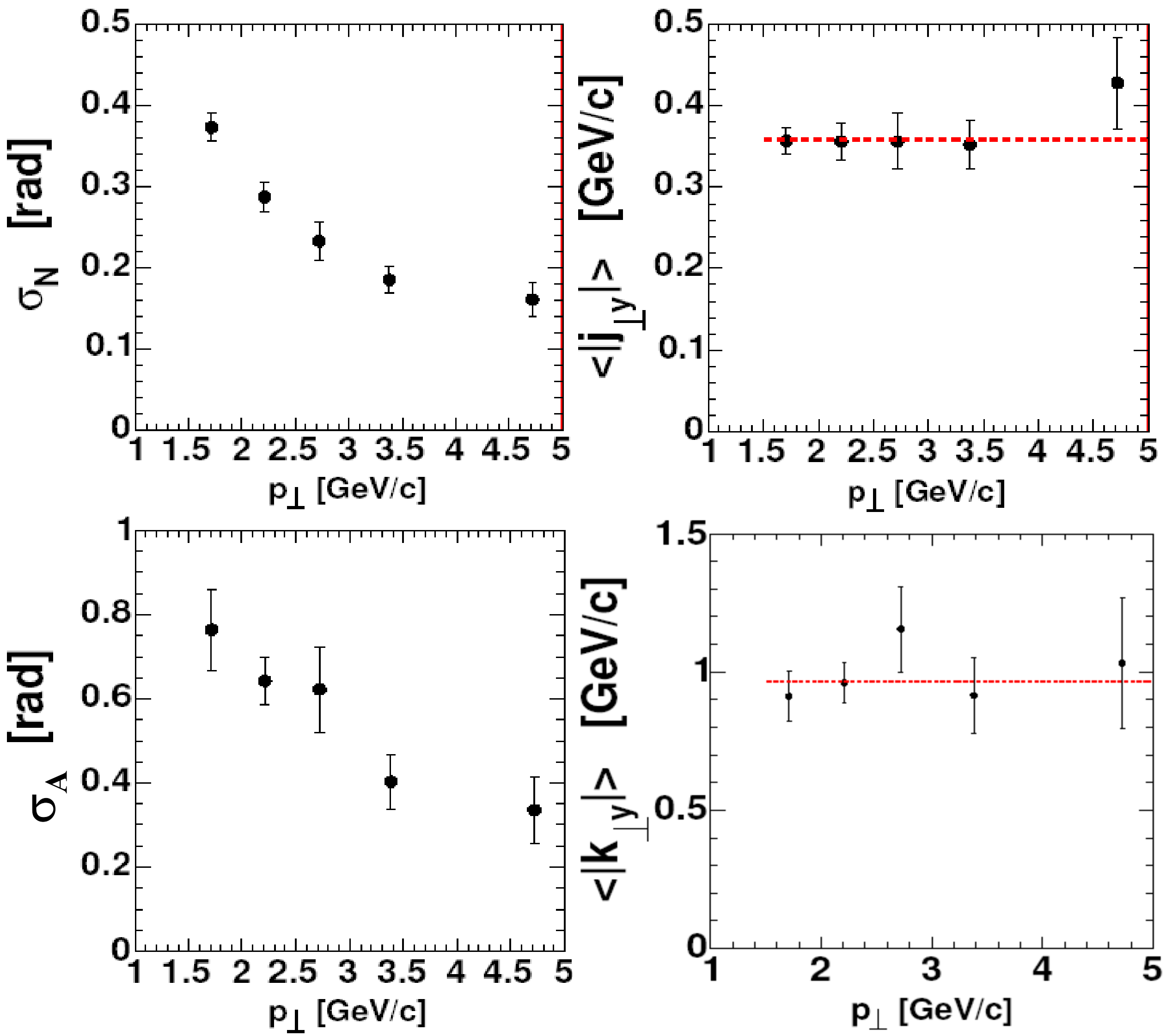
$$\langle|k_{Ty}|\rangle \approx \langle p_T\rangle\sqrt{\sigma_A^2 - \sigma_N^2}$$

However, inspired by Feynman, Field, Fox and Tannenbaum (see *Phys. Lett. 97B (1980) 163*) we derived more accurate equation

$$\boxed{\langle z_{trigg}\rangle\langle|k_{Ty}|\rangle = \frac{\langle p_T\rangle}{\sqrt{2}\,x_h}\sqrt{\sin^2\sqrt{\frac{2}{\pi}}\sigma_A - (1+x_h^2)\langle|j_{Ty}|\rangle^2}}$$

$x_h = p_{T,assoc} / p_{T,trigg}$

σ_N ,σ_A $\rightarrow \langle|j_{Ty}|\rangle$, $\langle|k_{Ty}|\rangle$ in pp data



$$\langle k_\perp{}^2\rangle_{pp} = \langle k_\perp{}^2\rangle_{vac}$$

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$\langle|j_{Ty}|\rangle$ = 359±11 MeV/c

$\langle|k_{Ty}|\rangle$ = 964±49 MeV/c

Both $\langle|j_{Ty}|\rangle$ and $\langle|k_{Ty}|\rangle$ in very good agreement with previous measurements:

PLB97 (1980)163

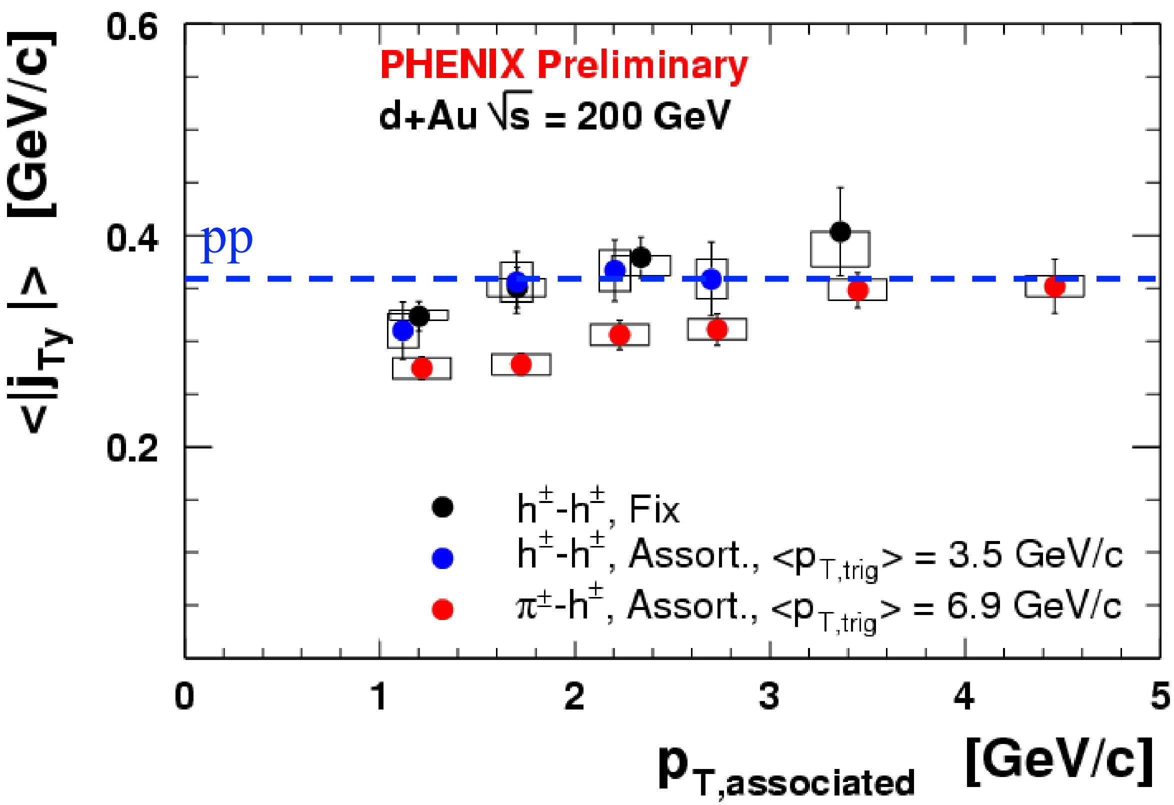
PRD 59 (1999) 074007

From pp to dAu

$$\langle k_\perp{}^2 \rangle_{\text{dAu}} = \langle k_\perp{}^2 \rangle_{\text{vac}} + \langle k_\perp{}^2 \rangle_{\text{IS nucl}}$$

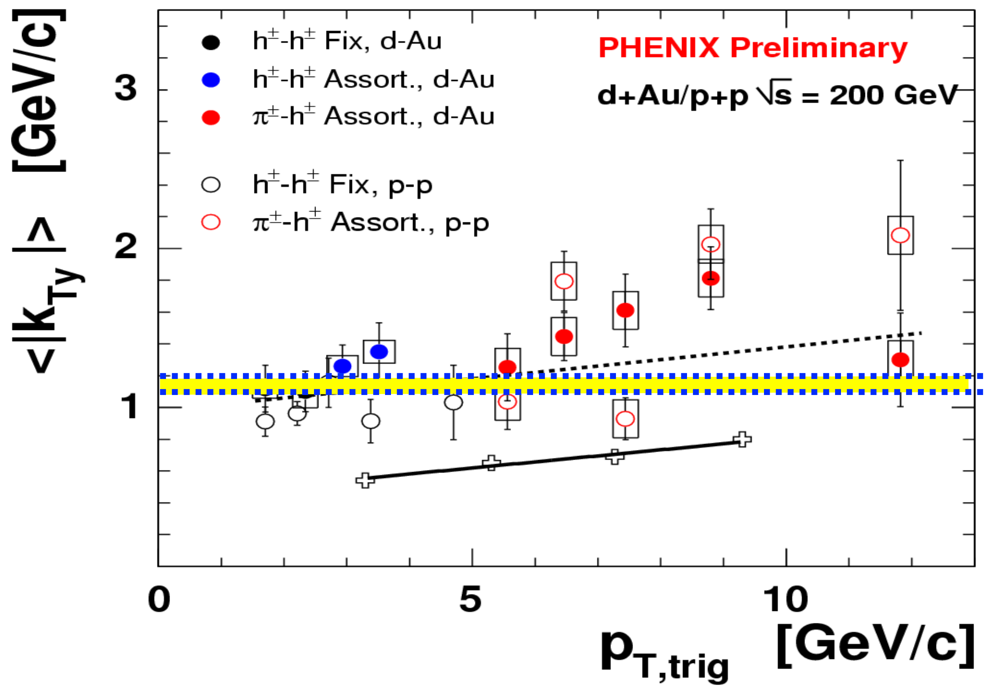
$\langle |k_{Ty}| \rangle$ carries the information on the parton interaction with cold nuclear matter.

$\langle |j_{Ty}| \rangle$ should be the same as in pp – systematic cross check



$\langle|k_{Ty}|\rangle$ from pp and dAu

$$\langle\Delta \mathbf{k}_T^2\rangle_{IS} = \mu^2/\lambda_{eff}\langle L\rangle_{IS}$$ I.Vitev nucl-th/0306039



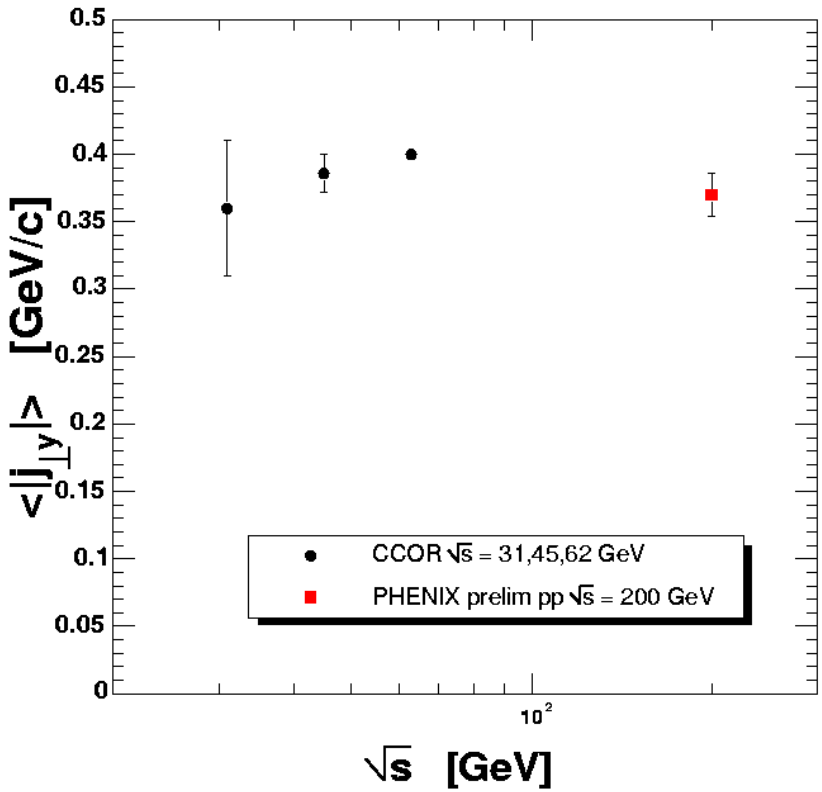
No significant k_T-broadening seen in dAu data

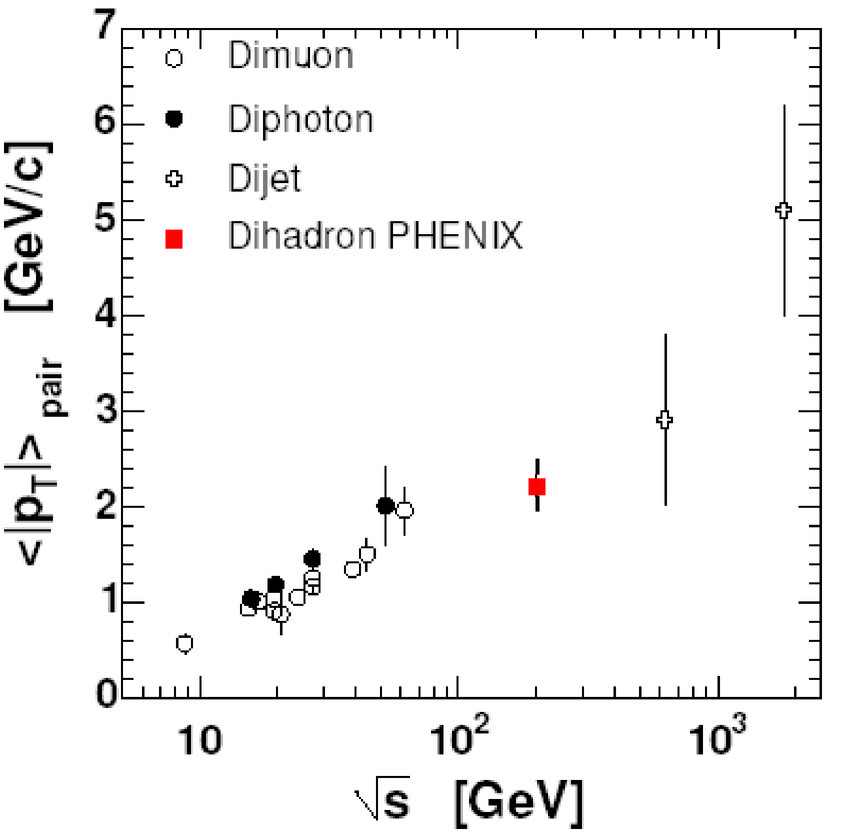
$\langle z\rangle$ =0.75 value taken from pp data

Mike T. *et. al.* Phys. Lett. B97, 163 (1980) $\sqrt{s}$ = 63 GeV

Comparison to outside world

PHENIX preliminary





A.L.S. Angelis et al ,

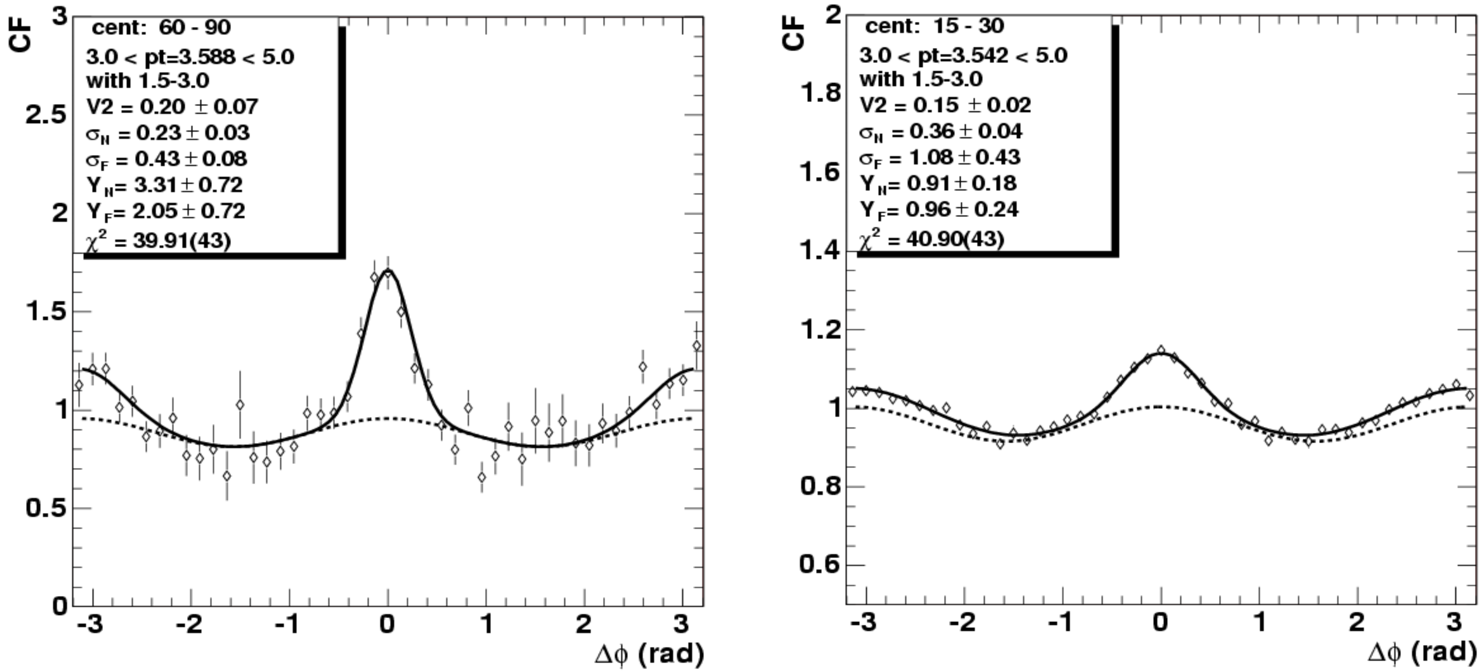
Phys. Lett. B97, 163 (1980)

L. Apanasevich et al.,

Phys. Rev. D59, (1999)

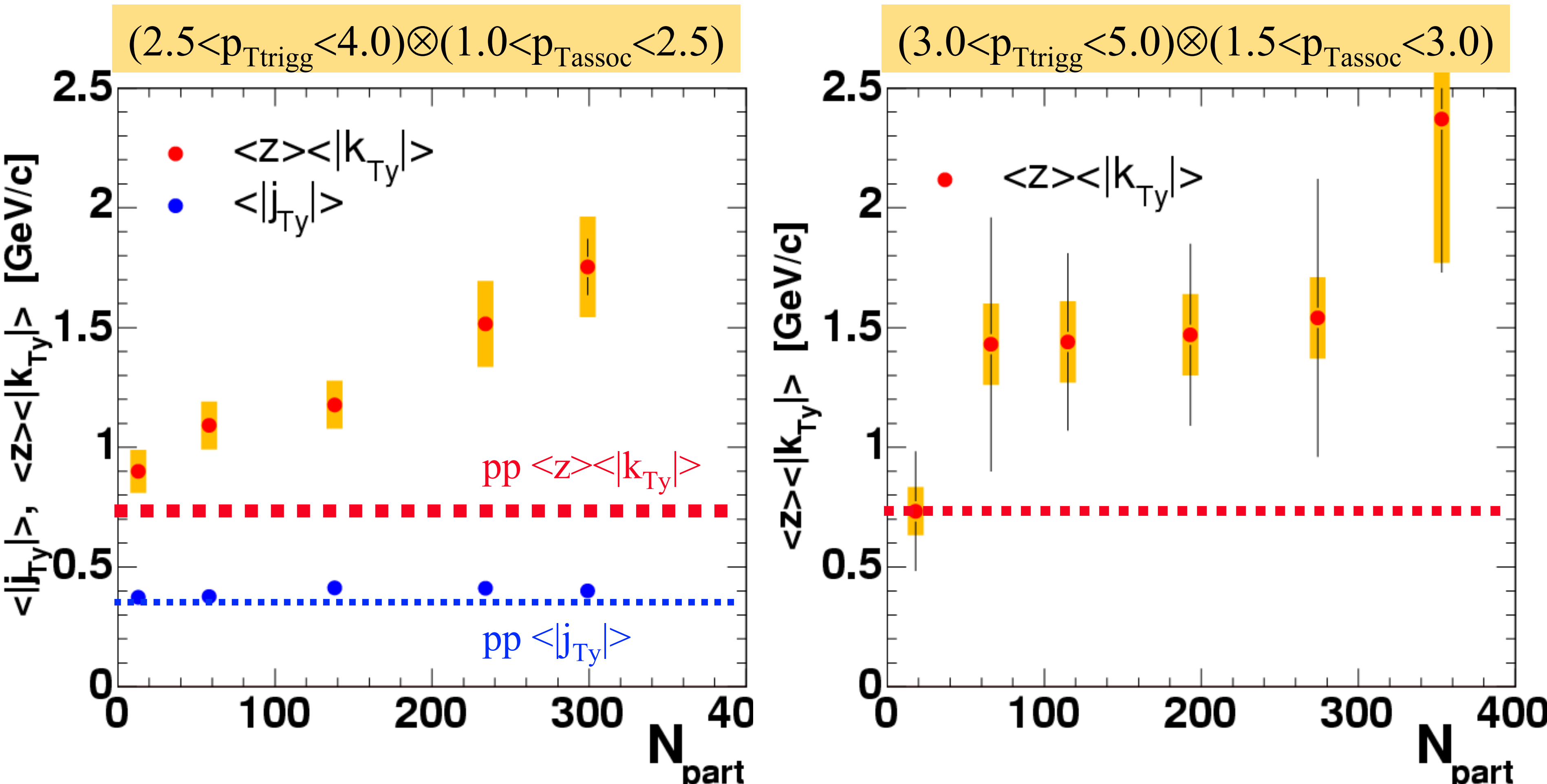
AuAu $\langle|j_{Ty}|\rangle$ and $\langle z\rangle \langle|k_{Ty}|\rangle$ from CF

$$\langle k_\perp^{\ 2}\rangle_{AA} = \langle k_\perp^{\ 2}\rangle_{vac} + \langle k_\perp^{\ 2}\rangle_{IS\ nucl} + \langle k_\perp^{\ 2}\rangle_{FS\ nucl}$$



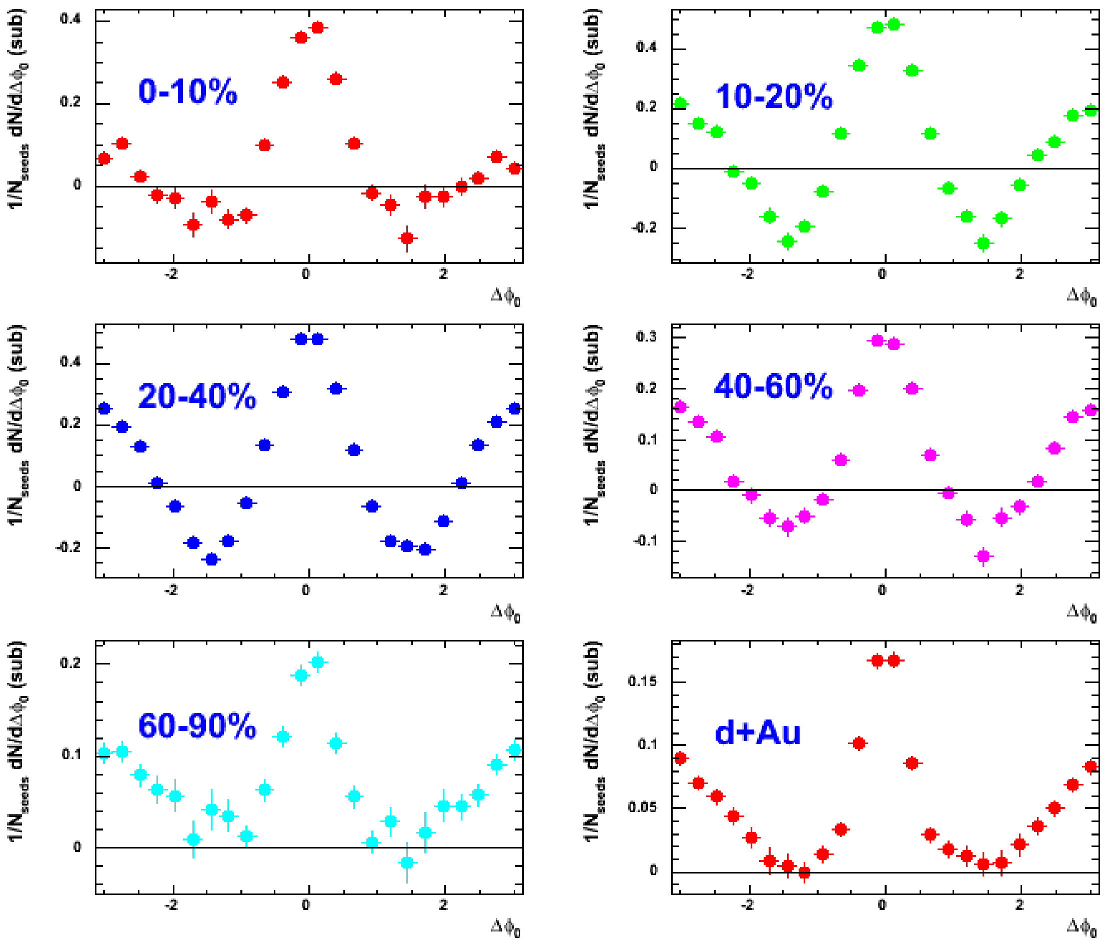
$$\text{Fit} \propto \underbrace{(1+2\, v_2^{\,2} \cos(2\Delta\varphi))}_{\text{AuAu}} \otimes + \underbrace{Y_N\, \text{Gauss}(0,\sigma_N) + Y_F \text{Gauss}(\pm\pi,\, \sigma_F)}_{\text{pp}}$$

AuAu $\langle|j_{Ty}|\rangle$ and $\langle z\rangle \langle|k_{Ty}|\rangle$ from CF

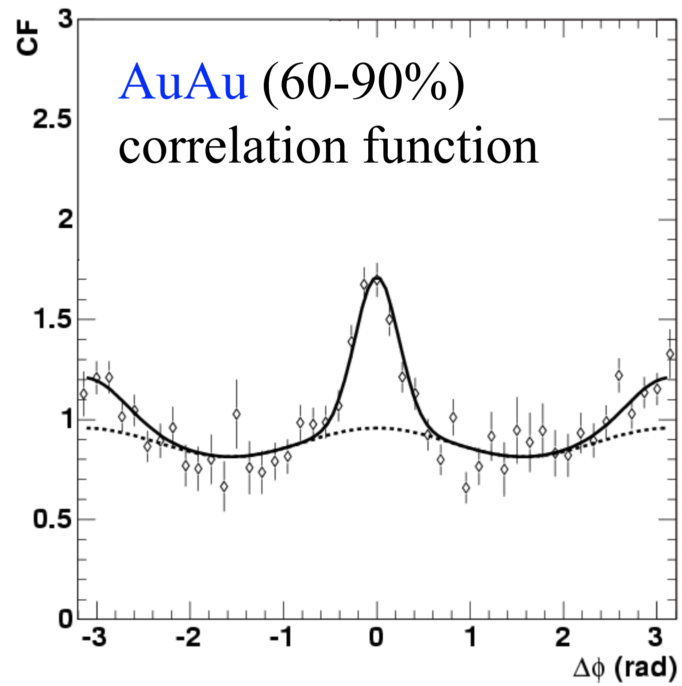


There seems to be significant broadening of the away-side correlation peak which persists also at somewhat higher p_T range.

AuAu yield



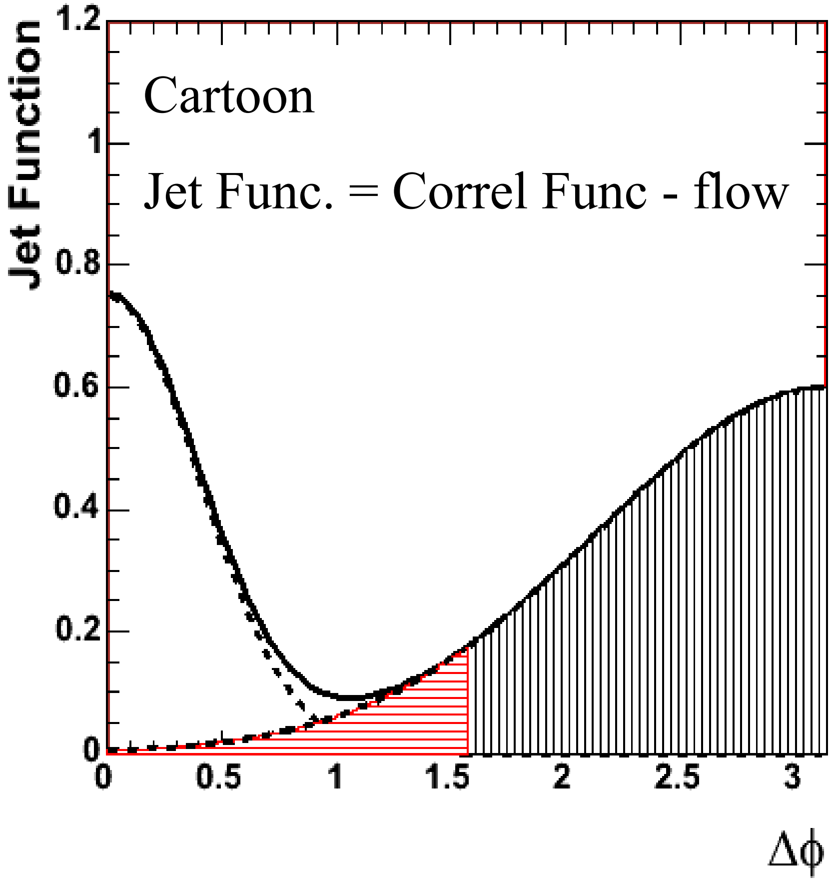
Subtracted dN/dΔφ integrating from 0-90, 90-180 to remove the v_2 component.

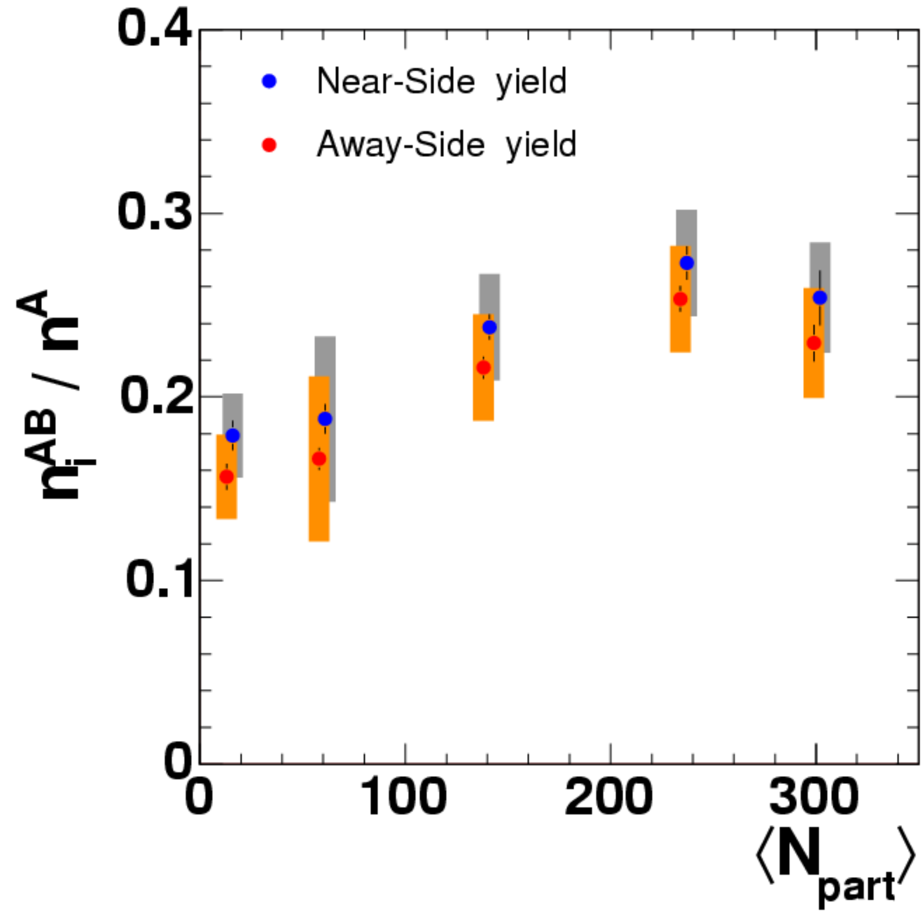


(2.5<p_{Ttrigg}<4.0)⊗(1.0<p_{Tassoc}<2.5) GeV/c

AuAu associated yields

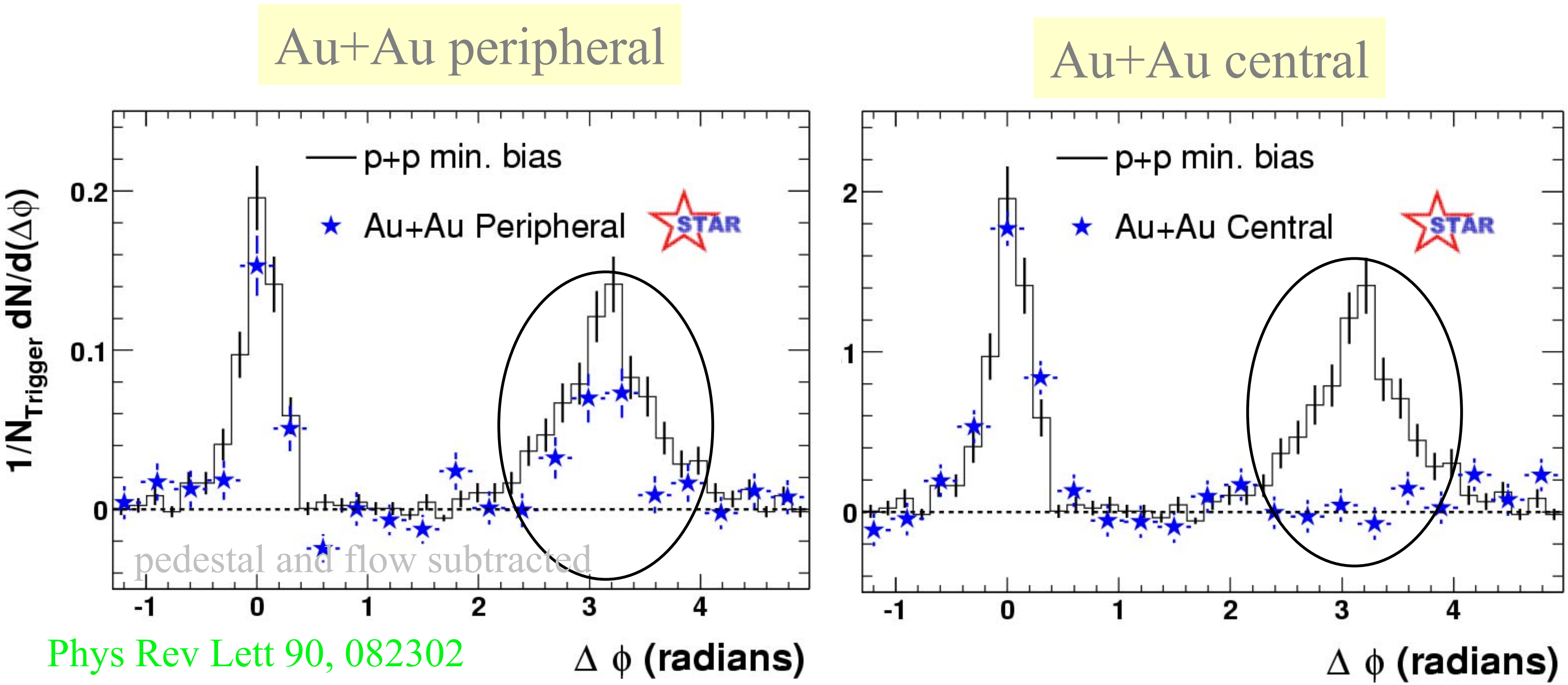
$(2.5<p_{Ttrigg}<4.0)\otimes(1.0<p_{Tassoc}<2.5)$ GeV/c





Note p_T is rather low; associated particle yields increase with centrality

Azimuthal distributions in Au+Au

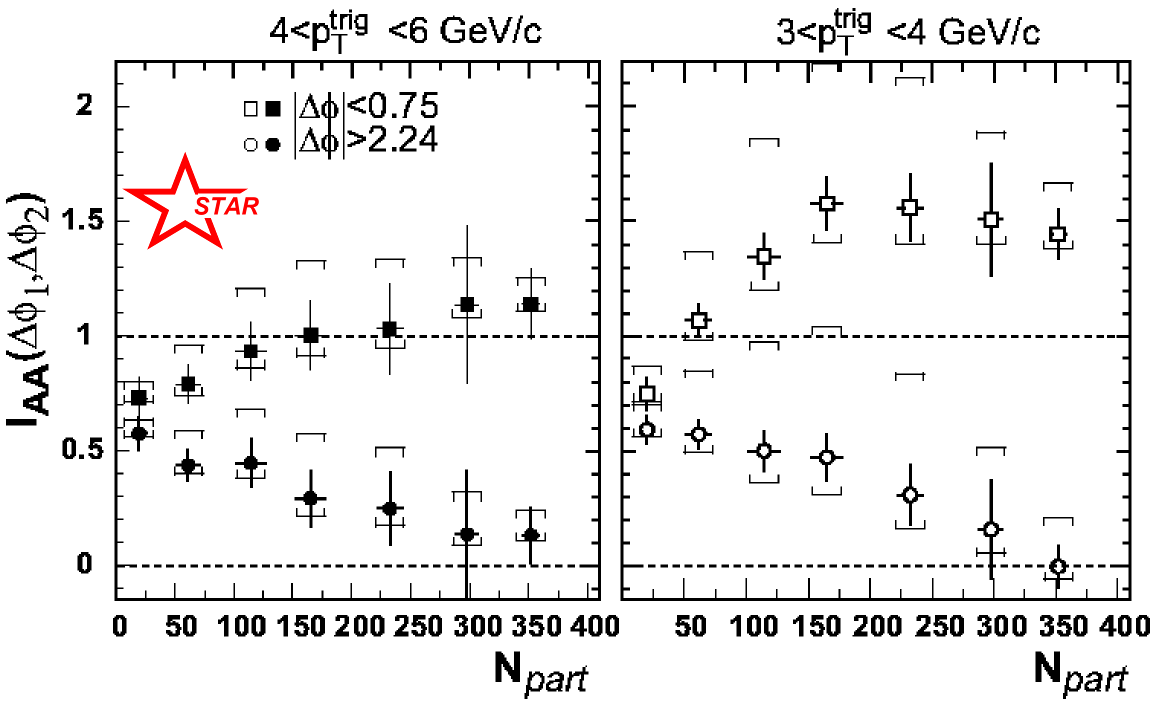


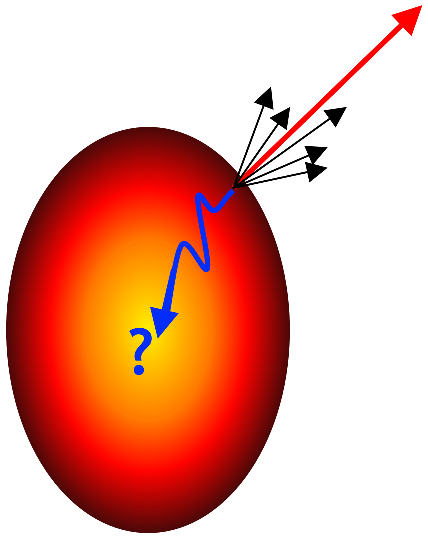
Phys Rev Lett 90, 082302

Near-side: peripheral and central Au+Au similar to p+p

Strong suppression of back-to-back correlations in central Au+Au

STAR jets and away-side quenching





Hint of surface emission ?

Nucl-ex/0210033

Or, the jets do make it through, but they scatter a lot and shake off couple of gluons below LPM threshold ?

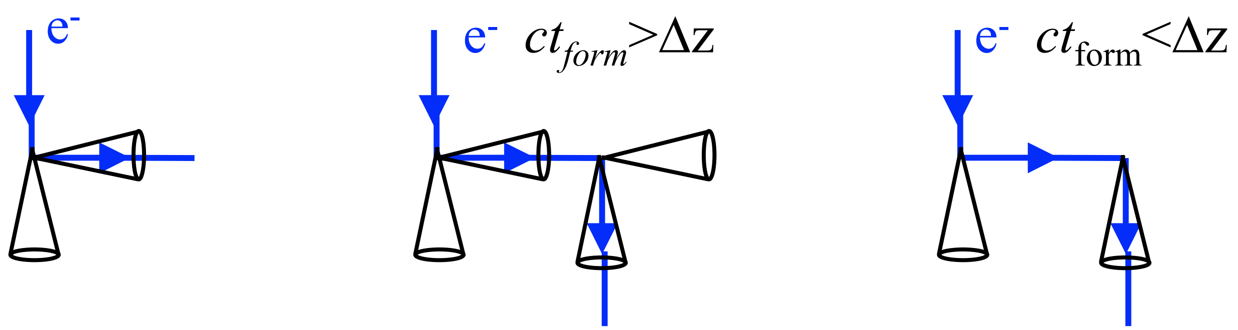
Induced gluon radiation – LPM effect

Formation time: elmag bremsstrahlung - field regeneration - well understood in QED.

Electron deep scattering – two cone of radiation:

1) surrounded field shaken off – direction of an initial e^- momentum

2) regeneration of the new field "coat" – final e^- momentum

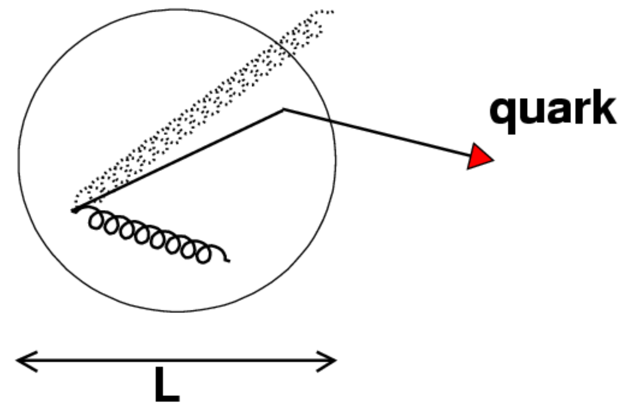


Formation time - gluon energy cut-off

Hadronization may happen only after full field regeneration.

$t_{form} = \gamma t = E/m_{constituent}\, R_{had}$

at confinement scale $m_{constituent} = \sqrt{\langle k^2_T \rangle} \approx 1/\ R_{had}$



$$t_{form} \approx E.R^2_{had} = E/\langle k^2_T \rangle$$

In order to radiate gluon, formation time $\tau^g_{form} \approx \omega/p^2_{T\omega}$ has to be shorter than L.

Nonperturbative estimate for the parton's transverse momentum due to the interaction with QCD medium

$$p^2_{T\omega} = \mu^2 L/\lambda$$

μ= transverse momentum kick per collision
λ=mean free path

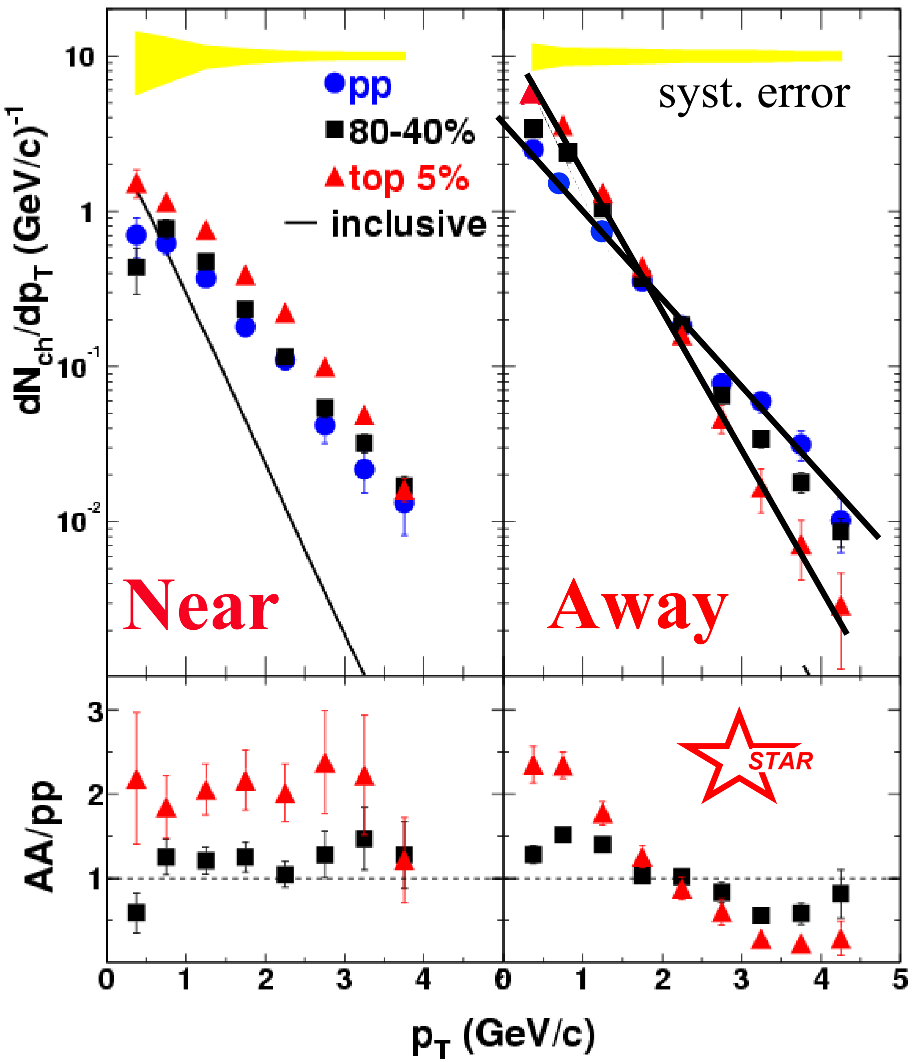
$\omega = \mu^2 L^2/\lambda$ energy loss of fast parton $\Delta E \propto \mu^2 L^2/\lambda$

p_T distributions on near and away side from STAR

Fuqiang Wang QM04

Near side:

Overall enhancement from pp to AA



Away side:

energy from initial parton seems to be converted to lower p_T particles

reminiscent of energy loss predictions

Apparent modification of the fragmentation function ?

Summary and conclusions

Systematic of jet production and fragmentation in pp, dAu and AuAu collisions:

- the slope of the fragmentation function in pp.
- σ_N , σ_A , $\langle|j_{Ty}|\rangle$ and $\langle|k_{Ty}|\rangle$ in pp, dAu, AuAu.

We found:

- Good agreement of the jet properties in pp collisions with other experiments.
- dAu $\langle j_T \rangle$ and $\langle k_T \rangle$ consistent with pp.
- In AuAu significant k_T - broadening with centrality.
- Yield of away side associated particles is suppressed at p_T>2GeV/c and shows rising trend with N_{part} below 2GeV/c. Remnant of high-p_T jets - hint for jet-rescattering rather than disappearance ?

Next step:

- map out this trend to explore “jet-quenching balance function”.
- Explore the AuAu fragmentation function.

Backup slides

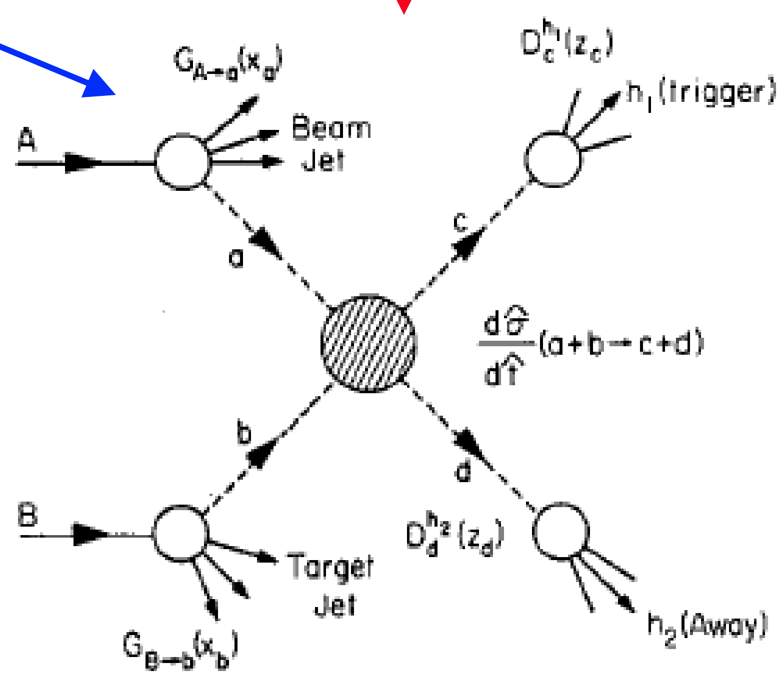
pQCD collinear factorization

Production yield in hard-scattering regime factorizes

$$\sigma_{AB \to hX} \propto f_{a/A}(x_a,Q^2{}_a) \otimes f_{b/B}(x_b,Q^2{}_b) \otimes \sigma_{a\,b \to cd} \otimes D_{h/c}(z_c,Q^2{}_c)$$

Parton distribution function

Fragmentation function

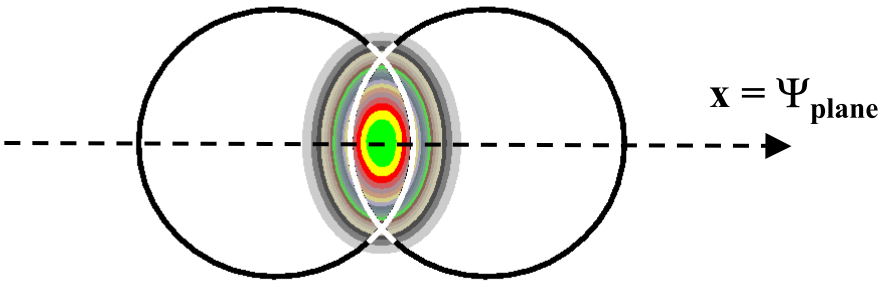


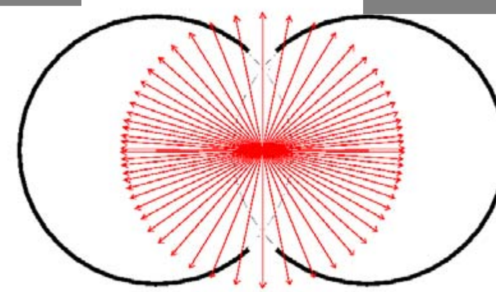
$D_{h/c}(z_c,Q^2{}_c) \approx$ **production probability of hadron h (momentum fraction $z_c = p_{Th}/p_{Tc}$) from parton c**

In AA some algebra of v2+jets needed

In AuAu collisions the situation is more complicated by presence of "global" correlations induced by nuclear geometry - called elliptic flow.

multiple scattering → larger pressure gradient in plane → more particles emitted in plane





spatial asymmetry
eccentricity

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

momentum asymmetry
elliptic flow - v2

$$v_2 = \frac{\langle p_x^2 - p_y^2 \rangle}{\langle p_x^2 + p_y^2 \rangle}$$

$$C(\Delta\varphi) = \frac{d^2N}{d\Delta\varphi} = \int_{-\pi}^{\pi} \frac{dN}{d\varphi} \frac{dN}{d(\varphi+\Delta\varphi)} d\varphi \qquad \frac{dN^{\mathrm{FLOW}}}{d\varphi} \propto (1 + 2v_2 \cos(2(\varphi - \Psi))) \oplus \frac{dN^{\mathrm{JET}}}{d\varphi} \propto Gauss(\varphi, \sigma)$$

$$C(\Delta\varphi) \propto (1 + 2v^2{}_2 \cos(2\Delta\varphi)) + Gauss(\Delta\varphi, \sqrt{2}\sigma) + Crossterm(\varphi_{\mathrm{jet}} - \Psi)$$

Flat if no correlation between Ψ_{plane} **and jet thrust**